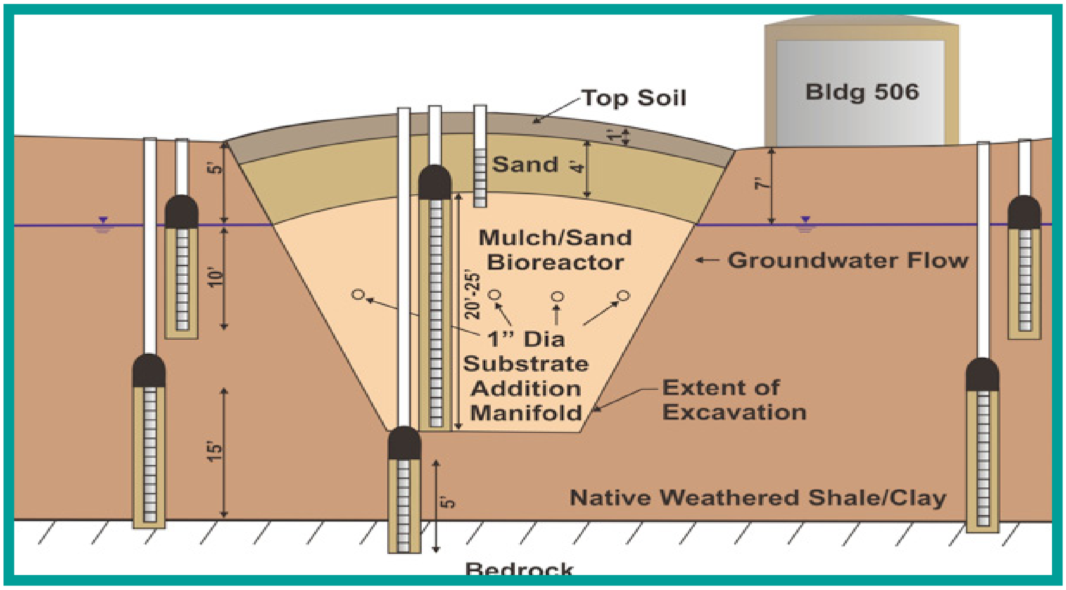
ESTCP
Cost and Performance Report

(ER-0019)



Impact of Landfill Closure Designs on Long-Term Natural Attenuation of Chlorinated Hydrocarbons

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ESTCP

ENVIRONMENTAL SECURITY
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COST & PERFORMANCE REPORT

Project: ER-0019

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ACRONYMS AND ABBREVIATIONS

µg/L	micrograms per liter
AFB	Air Force Base
AFCEE	Air Force Center for Environmental Excellence
bgs	below ground surface
CAH	chlorinated aliphatic hydrocarbon
CMS	Corrective Measures Study
DCE	dichloroethene
DNAPL	dense nonaqueous phase liquid
DO	dissolved oxygen
DOC	dissolved organic carbon
DoD	Department of Defense
DW	deeper well
ESTCP	Environmental Security Technology Certification Program
ET	evapotranspiration
ft/day	feet per day
ft/ft	foot per foot
ft/yr	feet per year
gpm	gallon(s) per minute
ID	inside diameter
LF-03	Landfill 3
LTM	long-term monitoring
mg/L	milligrams per liter
MNA	monitored natural attenuation
MSW	municipal solid waste
O&M	operation and maintenance
OM&M	operation, maintenance, and monitoring
ORP	oxidation-reduction potential
OU	operable unit
Parsons	Parsons Corporation
Parsons ES	Parsons Engineering Science
PCE	tetrachloroethene
PLFA	phospholipid fatty acids
PPE	personal protective equipment
PVC	polyvinyl chloride

ACRONYMS AND ABBREVIATIONS (continued)

QA/QC	quality assurance/quality control
QAPP	Quality Assurance Project Plan
RCRA	Resource Conservation and Recovery Act
SW	shallow well
TCA	tetrachloroethane
TCE	trichloroethene
USEPA	U.S. Environmental Protection Agency
VC	vinyl chloride
VFA	volatile fatty acid
VOC	volatile organic compound
VMP	vapor monitoring point

ACKNOWLEDGEMENTS

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1.0 EXECUTIVE SUMMARY

1.1 BACKGROUND

The subject of this cost and performance report is a pilot-scale field demonstration of a recirculation bioreactor at Landfill 3 (LF-03), Altus Air Force Base (AFB), Oklahoma. The purpose of constructing and operating the bioreactor was to demonstrate that a combination of organic material addition and accelerated leaching can rapidly reduce source area concentrations of chlorinated aliphatic hydrocarbons (CAH) in groundwater at unlined, closed landfills. Hundreds of landfills on Department of Defense (DoD) installations have generated CAH plumes in groundwater. Surface covers, which are intended to provide a barrier to prevent direct contact with waste material and minimize or eliminate infiltration of precipitation through the waste material (i.e., leachate formation), are the current method of choice to manage human and ecological risks at these sites (Bagchi, 1990). In some cases, impermeable covers may impede natural attenuation processes by reducing the quantity of organic-rich leachate that promotes the bioremediation of CAHs. The results of this project will provide environmental engineers with an additional perspective on treatment of dissolved volatile organic compound (VOC) plumes originating at unlined landfills (and at non-landfill source areas).

1.2 OBJECTIVES OF THE DEMONSTRATION

The bioreactor demonstration at Altus AFB had three primary objectives:

1. To demonstrate construction techniques and the instrumentation of two types of bioreactor cells that can be used for unlined and closed landfills:
    a. An active bioreactor that collects shallow groundwater and recirculates the groundwater through organic mulch to accelerate organic-rich leachate production and CAH biodegradation (Recirculation Bioreactor)
    b. A passive bioreactor that relies on natural groundwater flow and infiltration moving through an organic mulch layer to produce an organic-rich leachate (Passive Bioreactor).
2. To demonstrate that the bioreactor cells have a positive impact on the reductive dechlorination of CAH compounds as evidenced by trichloroethene (TCE) and dichloroethene (DCE) degradation without significant production or migration of vinyl chloride (VC). Leachate geochemistry and groundwater concentrations of CAHs were to be monitored beneath and immediately downgradient of each bioreactor to evaluate progress in achieving this objective.
3. To evaluate the longevity, potential costs, and benefits of landfill bioreactors for potential full-scale applications at Altus AFB and other DoD facilities.

1.3 DEMONSTRATON RESULTS

The primary regulatory driver for investigation and cleanup of hazardous waste at Altus AFB is Resource Conservation and Recovery Act (RCRA), Section 3008 (h). USEPA, Region 6, is the primary regulatory agency for the Base. LF-03, also referred to as Solid Waste Management Unit 7, was included in the base-wide RCRA Facility Investigation, Investigation Analysis, and Corrective Measures Study (CMS) (Earth Tech, 2002). The CMS recommended anaerobic bioremediation as the groundwater remediation alternative for the site. These regulatory considerations contributed to elimination of the passive bioremediation cell scenario as part of the final comparative bioreactor design, differing from the earlier bioreactor demonstration design discussed in the September 2003 Final Demonstration Work Plan.

The bioreactor was constructed by excavating a 30-ft by 30-ft by 11-ft-deep portion of the landfill near the suspected TCE source area and backfilling the excavation with a mixture of organic material and sand. A groundwater extraction trench was excavated into the shallow aquifer downgradient of the reactor cell and backfilled with gravel. Groundwater from the trench was extracted and distributed within the bioreactor cell using a drip irrigation system. Groundwater monitoring wells were installed within the bioreactor cell and in the aquifer adjacent to and beneath the test cell for monitoring concentrations of CAHs and geochemical/microbial indicator parameters. Five performance monitoring events were completed during the approximately 24-month pilot test.

During the five performance monitoring events, the bioreactor removal efficiencies for TCE and total chlorinated ethenes (sum of TCE, DCE, and VC) from recirculated groundwater ranged from 97 to 100% and 76 to 96%, respectively. A source of residual TCE in the subsurface upgradient of the bioreactor and above-average precipitation during a portion of the pilot test caused an influx of dissolved TCE, and an accumulation of TCE biodegradation daughter products (DCE and VC) in the monitored area adjacent to and beneath the bioreactor. Dissolved organic carbon (DOC) concentrations were elevated above the 20-milligram per liter (mg/L) threshold that is conducive for reductive dechlorination for approximately 6 months to a year in the deeper wells beneath the bioreactor, and for almost the entire 2-year duration of the pilot test in the shallow wells adjacent to the test cell. The presence of high sulfate concentrations in groundwater at LF-03 likely reduced the effectiveness of the bioreactor but did not prevent reductive dechlorination from occurring. Because of a continuing TCE source upgradient of the bioreactor and the accumulation of daughter products in the aquifer beneath and adjacent to the bioreactor, the objective of reducing CAH concentrations by 90% was not achieved.

1.4 IMPLEMENTATION ISSUES

Implementation of this technology requires excavation of vadose zone fill or waste, backfilling with a mulch/sand mixture, and installation of an infiltration gallery. In a full-scale implementation of this technology, it is likely that an area larger than the 900 sq ft tested in the pilot study would be excavated, and that a significant percentage of the soil/waste would require off-site disposal. In addition, if a vadose zone source area is removed, it is possible that a portion of the spoils would require disposal in a RCRA Subtitle C facility. Each of these conditions would affect the overall cost of the bioreactor technology. A cost analysis was performed to assess the impact of bioreactor size and off-site disposal requirements on the total net present value. The total net present value increases substantially with bioreactor size. For the small bioreactors evaluated (30 ft x 30 ft), the primary cost component was operation, maintenance, and monitoring (OM&M). For larger bioreactors, the capital costs contributed the most to the total net present value. In addition, the periodic cost of substrate replenishment represented a substantial portion of the total net present value. The greatest contributors to the capital cost were off-site disposal (transport and tipping fee) and bioreactor backfilling. If it is possible for the excavated soil to remain on site, then the capital costs would be substantially lower. However, it is expected that a technology which installs a bioreactor in a former source zone would result in off-site disposal of a significant percentage of the excavated material.

The cost analysis indicates that the mulch bioreactor technology has the potential for high costs to be incurred, depending on the size of the source area and the type of waste encountered. While this approach may be appropriate for well-defined, small, isolated source areas marked by shallow groundwater, it may not be the optimum approach for large landfills with multiple source areas.

Following completion of this demonstration project, Altus AFB has continued to operate the recirculation bioreactor and subsequently funded a project to add liquid carbon substrate and a bioaugmentation culture to the recirculation system. The goal of the follow-on project is to refresh the organic carbon supply and to determine if more complete and effective reductive dechlorination can be achieved.

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2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY DEVELOPMENT AND APPLICATION

Field and laboratory research over the past 10 years has discovered an important link between the rapidity and completeness of chlorinated aliphatic hydrocarbon (CAH) biodegradation and the quantity of dissolved organic carbon (DOC) that is comingled with CAH plumes (Wiedemeier et al., 1999). CAH plumes that are comingled with fuel spills and landfill-derived organics are much more likely to undergo biodegradation via the process of anaerobic reductive dechlorination. However, most military landfills containing CAH contaminants are over 30 years old and contain limited amounts of leachable organic material to continue the reductive dechlorination process.

The recirculation bioreactor installed for this project is an application of enhanced anaerobic bioremediation, which seeks to exploit anaerobic biodegradation processes to completely degrade contaminants to innocuous end products (Parsons, 2004). The bioreactor provides a source of leachable organic material for the CAH-contaminated aquifer, which is used by native microorganisms to create a highly reducing anaerobic treatment zone. It was intended that the leaching of organic carbon and bioremediation would be accelerated by the recirculation of groundwater through the bioreactor.

The carbon substrate used in the Landfill 3 (LF-03) bioreactor is primarily cellulose from a mixture of wood mulch and cotton gin trash. Sand was added to the mixture to improve hydraulic conductivity and reduce compaction in the test cell. Compared with soluble liquid carbon substrates (e.g., fructose, lactate, and molasses), solid carbon substrates, such as cellulose, are intended to be relatively long-lasting, slow-release sources of organic carbon.

The recirculation bioreactor at LF-03 was designed to promote direct anaerobic dechlorination of CAHs; however, it is likely that abiotic processes are also occurring. Biotic reductive dechlorination is the sequential removal of chlorine atoms and is the only common biological reaction known to degrade tetrachloroethene (PCE), TCE, tetrachloroethane (PCA), trichloroethane (TCA), carbon tetrachloride, and chlorinated benzenes with more than four chlorine atoms. Each chlorine atom that is removed in this process is replaced with a hydrogen atom. For example, chlorinated ethene reductive dechlorination proceeds sequentially from PCE (C_2Cl_4) to TCE (C_2HCl_3) to DCE ($C_2H_2Cl_2$) to VC (C_2H_3Cl) to ethene (C_2H_4).

2.2 PROCESS DESCRIPTION

Cross-sectional and plan views of the LF-03 recirculation bioreactor installed at Altus Air Force Base (AFB), LF-03, are shown on Figure 1. The recirculation bioreactor system is designed to extract approximately 2 to 3 gallons per minute (gpm) of water from the trench and distribute the water through a drip irrigation system equipped with approximately 120 drippers near the top of the bioreactor. Distributing the water through the mulch cell provides treatment of CAHs by anaerobic biodegradation processes within the bioreactor cell and increases the organic carbon concentration of water exiting the bioreactor to support enhanced bioremediation of CAHs in the aquifer.

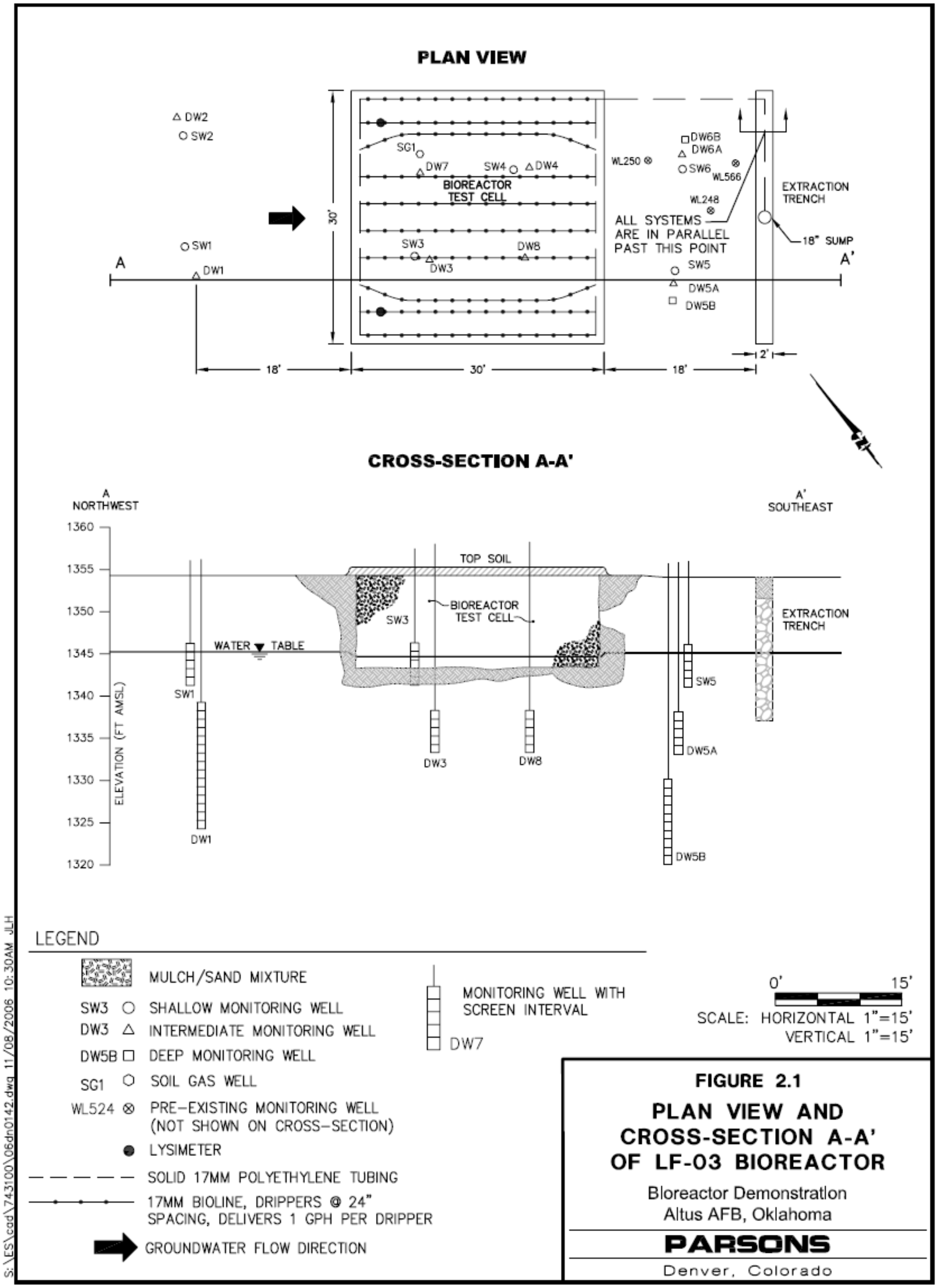

Figure 1. Plan View and Cross Section A-A' of LF-03 Bioreactore.

2.3 PREVIOUS TESTING OF THE TECHNOLOGY

Although the authors believe that the Altus AFB pilot bioreactor application that is the subject of this report is unique, the bioreactor concept is not new. “Bioreactor” is a generic term for a system that degrades contaminants using microorganisms. Bioreactors have been used in a wide variety of configurations to treat a variety of contaminants in multiple types of waste streams. Parsons (2006) provides a literature review that includes a summary of the bioreactor concept used 1) in municipal solid waste (MSW) landfills to accelerate the decomposition of waste and landfill gas generation; 2) for odor control from industrial, agricultural, and municipal sources of air emissions; 3) to biodegrade toxic compounds in liquid and vapor effluent streams from municipal and industrial processes and groundwater remediation systems; and 4) to treat CAH-contaminated groundwater in a passive, in situ biowall configuration.

2.4 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The application of a recirculation bioreactor for CAH source treatment as demonstrated at Altus AFB, LF-03, has several advantages over other remediation options and limitations that should be evaluated against the strengths of other applicable remediation technologies when choosing alternatives. These advantages and limitations are described below.

2.4.1 Advantages of the Technology

Recirculation bioreactors for CAH source treatment have several advantages over other remediation options, including:

- Excavation of contaminant source material during bioreactor construction can remove the majority of the contaminant mass present at the site if the location of the source material has been sufficiently defined.

- Groundwater is treated in situ by destructive processes rather than by a mechanical process such as air stripping that simply transfers contaminants to another medium.

- Recirculation allows enhanced dissolution of residual contaminant sources and increases the distribution of DOC. This is a significant benefit for heterogeneous, anisotropic subsurface environments such as the low permeability, fractured clay and shale present at LF-03.

- Delivery of organic carbon vertically through the bioreactor cell is more effective than through individual injection points in a fracture-flow environment because there is a higher likelihood of the organic substrate following the same migration pathways as the chlorinated solvents in a top-loaded system.

- The recirculation bioreactor provides both a water treatment system within the cell and an effective method for delivering organic carbon to the saturated zone.

The use of mulch as the carbon source utilizes locally available organic materials that are readily available and low cost.

- The bioreactor design demonstrated at Altus AFB, LF-03, had minimal operation and maintenance (O&M) requirements.

2.4.2 Limitations of the Technology

- The generation of relatively toxic daughter products, particularly VC, and the production of methane may be undesirable at some sites.

- The technology is best suited for sites with relatively shallow water tables where it is economical to excavate the source material in the vadose zone. However, it is feasible that this approach could also be successfully implemented at some sites with deeper water tables by allowing organic carbon-laden water to percolate through the vadose zone to the water table below the bottom of the bioreactor. This approach assumes that the organic carbon supply is not depleted (i.e., biodegraded) in the vadose zone prior to reaching the water table.

- The soluble organic carbon content in the mulch will decline over time and may need to be recharged (e.g., with a liquid organic substrate such as vegetable oil).

- The technology may not be well-suited for thick, sandy aquifers that require the removal of large volumes of water to control the contaminant plume and form a closed-loop system.

- When working in a landfill environment, there is an inherent possibility of encountering additional, previously unidentified contaminant source zones and hazardous materials. In such cases, increased contingency costs are to be expected.

- Conditions become less favorable for reductive dechlorination with increased distance vertically and laterally from the bioreactor cell. Site-specific conditions at LF-03 such as the high sulfate concentrations and shallow depth of the extraction trench likely contributed to this limitation. Other sites with more favorable geochemical conditions may have better performance at greater depths, but in general the technology demonstrated at LF-03 is better suited for sites where the desired remediation zone does not extend more than approximately 10 to 20 ft below the base of the bioreactor. An alternative technology such as organic substrate injection via vertical wells or temporary injection points may be better suited to remediate deeper zones.

3.0 DEMONSTRATION DESIGN

3.1 PERFORMANCE OBJECTIVES

Groundwater analytical data for the bioreactor test cell were evaluated to determine the overall effectiveness of the bioreactor in reducing dissolved chlorinated ethene concentrations. Performance objectives for the bioreactor are described in Table 1. The bioreactor was a means for adding carbon substrate to the shallow groundwater at LF-03 and produced the reducing conditions that are necessary for reductive dechlorination to occur. The presence of high sulfate concentrations in groundwater at LF-03 likely reduced the effectiveness of the bioreactor but did not prevent reductive dechlorination from occurring. Because of a continuing TCE source upgradient of the bioreactor and the accumulation of daughter products in the aquifer beneath and adjacent to the bioreactor, the objective of reducing CAH concentrations by 90% was not achieved. The accumulation of DCE and VC in the shallow aquifer may likely be due to kinetic disparity where the intermediate dechlorination product is being generated faster than it is degraded, and not to an absence of appropriate dechlorinating microorganisms (Parsons, 2004).

Table 1. Performance Objectives, Bioreactor Demonstration, Altus AFB, Oklahoma.

Type of Performance Objective	Primary Performance Criteria	Expected Performance (Metric)
Quantitative	*Geochemical and Microbial Enhancement in LF-03 Saturated Zone:* Determine the chemical quality of leachate that can be produced when groundwater is recirculated through mulch material.	Reduced dissolved oxygen (DO), nitrate/nitrite, and sulfate concentrations; Increased DOC (including volatile fatty acids [VFA]), ferrous iron, and methane concentrations in the circulating groundwater; and evidence of microbial enhancement (via phospholipid fatty acid [PLFA] analyses).
Quantitative	*Contaminant Reduction*: Determine if the mulch bioreactor provides enough organic substrate to drive reductive dechlorination of CAHs as recirculated leachate passes through the bioreactor. Measured influent levels of TCE, DCE, VC, chloride, and ethene (as the leachate enters the top of the bioreactor) will be compared to levels of these constituents measured beneath and downgradient from the mulch bioreactor.	TCE being converted to DCE, and DCE being converted to VC, ethene, carbon dioxide, and chloride ions. Goal is a 90% reduction in the total CAH molar concentrations of groundwater in downgradient monitoring wells.
Quantitative	*Factors Affecting Technology Performance*: Identify how stratigraphy, groundwater geochemistry, changes in geochemistry during recirculation, and bioreactor design factors affect bioreactor performance.	Conclusions will be based on observations of groundwater mounding in the test cell, changes in groundwater geochemistry during recirculation, maintenance requirements, and bioreactor effectiveness.
Qualitative	*Reliability and Maintenance Requirements*: Evaluate reliability of solar pump and drip irrigation system for bioreactor applications.	Conclusions will be based on observations of solar pump and drip irrigation system reliability and O&M requirements.
Qualitative	*Scale-up Constraints and Technology Application*: Determine if the recirculation bioreactor design is appropriate for other landfills, both at Altus AFB and other DoD installations, and evaluate which types of climates, hydrogeologic settings, and landfill situations are best suited for this bioreactor design.	Conclusions will be based on 1) observations of bioreactor maintenance requirements and performance and 2) evaluation of any design modifications necessary or desirable for full-scale bioreactor implementation.

3.2 TEST SITE SELECTION

LF-03 in Operable Unit 1 (OU-1) at Altus AFB was selected as the landfill site for a recirculation bioreactor demonstration because of the favorable characteristics of the site and because Altus AFB personnel were receptive and supportive of the bioreactor pilot test and viewed it as a “win-win” situation for this ESTCP project and the base. Altus AFB personnel discussed this demonstration project with USEPA oversight personnel and obtained their support. However, the final bioreactor design, although favorable toward addressing the base’s regulatory goals and objectives, no longer included the original design features and objectives set forth in the ESTCP demonstration plan. Consequently, along with unanticipated contaminant source conditions, various ESTCP bioreactor demonstration performance objectives remain unresolved. Characteristics of an ideal candidate landfill site for the field pilot test are described in Table 2 along with the conditions present at Altus AFB, LF-03.

Table 2. Characteristics Leading to Selection of Altus AFB Site LF-03 for the Bioreactor Pilot Test, Bioreactor Demonstration, Altus AFB.

Desired Pilot Test Site Characteristic	Actual Condition at Altus AFB, LF-03
Dissolved CAH plume present in groundwater beneath the landfill, with a significant, continuing contaminant source in the landfill interior.	Available information suggested that the source area for the LF-03 CAH plume was located in the immediate vicinity of the current bioreactor test cell; therefore, this site provides an example of how a bioreactor can be installed in a limited landfill source-area “hotspot” excavation near the upgradient end of a substantial CAH plume.
PCE and/or TCE are primary risk-driver chemicals and are present in groundwater at relatively high concentrations (>100 micrograms per liter [µg/L]).	TCE is the primary contaminant of concern in groundwater beneath LF-03, with source area concentrations greater than 10,000 µg/L.
Remedial goals cannot be met within an acceptable time frame via monitored natural attenuation (MNA).	Reductive dechlorination of TCE was primarily limited to areas of OU-1 with commingled fuel hydrocarbon contamination (Parsons Engineering Science [Parsons ES], 1999). TCE biodegradation was not proceeding past the transformation to DCE, and VC was not detected. TCE is the primary component of the dissolved phase plume.
A final closure cover has not been designed or installed, or a vegetative (evapotranspiration [ET] type) cover is already in place.	Neither a final closure cover nor an ET cover is present at LF-03; the site is covered with native vegetation.
Remedial goals can be met with an ET cover (i.e., a low-permeability cover is not required). Either precipitation rates are sufficiently low that the infiltration-control properties of the ET cover would not be overwhelmed, or a significant portion of the contaminated waste lies below the average water table (i.e., infiltration is not the only source of water for plume generation).	There is no immediate plan to place an engineered cover on LF-03. It appears that a significant source of TCE remains in the subsurface. The vertical extent of the residual source is not known, but it appears to reside at least partially in the vadose zone.
Anaerobic conditions are present in the core of the dissolved plume, and the plume core can be contained at reasonable expense by extracting a flow that can be reapplied within the landfill (e.g., shallow depth to groundwater, limited-transmissivity aquifer). The presence of an existing groundwater collection system would be beneficial from a cost standpoint but is not required.	Background DO concentrations at the LF-03 bioreactor site averaged 0.8 mg/L (Parsons ES, 1999). The shallow depth to groundwater (6 to 9 ft below ground surface [bgs]), the limited thickness of the transmissive portion of the saturated zone (approximately 20 to 30 ft), and the fine-grained nature of the aquifer (clay and shaley clay) made it feasible to cost-effectively construct a shallow groundwater interceptor trench for leachate capture and recirculation.

3.3 TEST SITE HISTORY/CHARACTERISTICS

LF-03 is located in the northeastern portion of the base in a remote area adjacent to airfield taxiways. From 1956 through 1965, LF-03 received waste materials including garbage, wood, metal, paper, and shop wastes. After 1965, LF-03 received construction debris, concrete, brush, and several drums of paint waste. From 1956 to 1965, waste at LF-03 was buried in trenches with depths ranging from 6 to 8 ft bgs.

Shallow groundwater at the base occurs under unconfined conditions and generally flows to the southeast. Shallow groundwater in the LF-03 bioreactor area occurs at depths of 4 to 5 ft bgs during the wet winter and spring months and 5 to 9 ft bgs during the dry summer and fall months. The groundwater surface slopes toward the southeast with an average horizontal hydraulic gradient of approximately 0.003 foot per foot (ft/ft) (Parsons, 1999).

The hydraulic conductivity of the uppermost water-bearing zone was estimated to range from 8.4 to 20 feet per day (ft/day) in the fractured clay overburden (upper zone). Using this range of hydraulic conductivity values, a measured lateral hydraulic gradient of 0.003 ft/ft, and an estimated effective porosity (5%), the advective groundwater flow velocity in the overburden clay is calculated to range from 0.50 to 1.20 ft/day [183 to 438 feet per year (ft/yr)].

Since 1984, several remedial investigations have been completed at and downgradient of LF-03. Groundwater quality data indicate that TCE and *cis*-1,2-DCE are the most prevalent CAHs in OU-1 groundwater in terms of both areal extent and concentration. In March 2003, TCE and *cis*-1,2-DCE were detected at well WL250 at concentrations of 17,900 and 1,330 µg/L, near the suspected LF-03 source area. The TCE plume originates at LF-03 (in the vicinity of monitoring well WL250) and extends southeastward approximately 4,000 ft to the base's eastern boundary. The LF-03 bioreactor is located immediately upgradient of hot-spot well WL250, as this was believed to be the most likely location for CAH source material.

3.4 PHYSICAL SETUP AND OPERATION

The LF-03 recirculation bioreactor system consists of four primary components: an organic mulch cell excavated into the saturated zone, a groundwater collection trench, a groundwater recirculation system, and a monitoring network. Construction of the bioreactor system and monitoring network occurred over 10 days in October 2003. The bioreactor cell is a 30 ft by 30 ft square excavated to a depth of 11 ft bgs. Excavated soil containing landfill debris was segregated upon removal from the excavation. Landfill debris was encountered from near the ground surface to a depth of at least 8 ft bgs; however, there was no indication of CAH source material. Soil that did not contain landfill debris was spread adjacent to and on top of the bioreactor; a total of 142 tons of soil that contained landfill debris was characterized and disposed of as nonhazardous waste at a RCRA subtitle D landfill.

The backfill material placed in the cell was a mixture of 50% wood mulch, 40% sand, and 10% cotton burr trash, by volume. These three components were combined using a backhoe and front-end loader and used to backfill the cell from 11 to 12 ft bgs. Additional backfill was needed to fill the cell to grade and wood mulch (only) was utilized as it was the most readily available and least expensive component of the mixture. The cell was capped with two layers of geotextile fabric to prevent topsoil from migrating downward into the organic material. The groundwater distribution piping was installed between the geotextile layers. A 2-ft-thick layer of topsoil (set aside during the initial excavation) was placed over the cell and native grasses were allowed to reestablish themselves.

The groundwater collection trench was excavated 18 ft downgradient of the bioreactor cell using a backhoe. The trench is 2 ft wide, 30 ft long, and 18 ft deep in the center. An 18-inch inside diameter (ID), slotted, polyvinyl chloride (PVC) pipe was installed vertically in the middle of the trench to act as the sump. The entire trench was backfilled around the sump to within 2 ft of the surface with ½-inch plus washed angular gravel.

The groundwater distribution system consists of a solar-powered Grundfos submersible pump, instrumentation, valves, and duplicate distribution headers. The pump can produce a flow of 2 to 3 gpm during peak daylight hours and does not operate during the night or periods of low light. Water is discharged from the pump into a 1-inch poly tube and through a pressure relief valve, flow totalizer, strainer, and pressure gauge prior to reaching the distribution headers. The entire system is buried at least 2 ft bgs for freeze protection. The instrumentation and valves are accessible through a series of valve boxes.

System startup occurred immediately after completion of the baseline sampling event on November 16, 2003. Startup consisted of turning the pump on and ensuring that pressure and flow were within the desired ranges. No modifications to the system were necessary.

3.5 SAMPLING AND MONITORING

The monitoring network consists of 16 groundwater monitoring wells, one soil vapor monitoring point (VMP), two gravity lysimeters, and one distribution system sampling point (Figure 1). Shallow monitoring wells (SW) were installed upgradient, within, and downgradient of the cell. Deeper monitoring wells (DW) were installed upgradient, below, and downgradient of the cell. The bioreactor was designed to require minimal oversight and maintenance. The solar pump is the only mechanical equipment at the site. Altus AFB and Parsons personnel visited the site periodically to check that the pump was operating and record pressure and flow data. Performance monitoring groundwater sampling events were completed 3, 7, 13, 17, and 24 months after system start-up. Parsons operated, maintained, and monitored the bioreactor cell at LF-03 until the final sampling event on November 11, 2005. Altus AFB has continued to operate the system since November 11, 2005.

The sampling plan for the LF-03 bioreactor was developed following USEPA guidance for documenting the natural attenuation of CAHs (USEPA, 1998) and using prior experience monitoring enhanced bioremediation sites. The bioreactor was sampled to monitor the chemical and geochemical conditions in the groundwater impacted by the pilot test. The objective of this monitoring was to evaluate the impact of the bioreactor on the anaerobic dechlorination of CAHs in groundwater and the groundwater geochemistry near the LF-03 source area.

Groundwater samples were collected using a low-flow "micropurge" technique where water quality stabilization parameters were monitored prior to sampling. Soil gas samples were collected for fixed-base laboratory analysis using Summa canisters. The procedures used prior to and during each of the groundwater and soil gas monitoring events to ensure that representative samples were obtained are described in Appendix B of the Final Technical Report (Parsons, 2006).

Two lysimeters installed above the water table in the bark mulch bioreactor were used to verify that water was infiltrating into the bioreactor at the downstream ends of the drip lines. During each of the performance monitoring events the lysimeters were purged and were observed to recharge.

3.6 ANALYTICAL PROCEDURES

Groundwater samples were analyzed for VOC and a suite of geochemical and microbial indicator parameters. Groundwater samples, as well as the quality assurance/quality control (QA/QC) samples, were analyzed at both fixed-base commercial laboratories and in the field using field test kits (e.g., Hach® portable colorimeter or titration kits in accordance with manufacturer-specified procedures) and direct-reading meters. Soil gas samples were analyzed for VOCs, oxygen, carbon dioxide, and methane at a fixed-base commercial laboratory. The Quality Assurance Project Plan (QAPP) is available in Appendix C of the Final Technical Report (Parsons, 2006).

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4.0 PERFORMANCE ASSESSMENT

4.1 PERFORMANCE DATA

Table 3 summarizes the performance data collected during this demonstration. The analytical data that were collected include both direct and indirect biodegradation indicators. Analysis of chlorinated ethene concentrations provides direct evidence of contaminants being biodegraded. Concentrations of geochemical parameters that are widely recognized and accepted indicators of the degree to which groundwater geochemical conditions are conducive to biodegradation of chlorinated solvents (e.g., see the Technical Protocol for Evaluating Natural Attenuation of Chlorinated Solvents in Groundwater [USEPA, 1998]) provide indirect evidence of biodegradation. In addition to these commonly targeted natural attenuation indicator parameters, more recently developed and relatively innovative biological indicator parameters (i.e., VFAs and PLFAs) were targeted for analysis. This section presents a summary of the primary performance data collected during the pilot test. A complete presentation of the data collected during the pilot test is available in Section 4 of the Final Technical Report (Parsons, 2006).

Table 3. Performance Data Summary Bioreactor Demonstration, Altus AFB.

Altus LF-03 Pilot-Scale Recirculation Bioreactor	
Types of samples collected	Groundwater samples were collected from monitoring wells installed within, beneath, and adjacent to the bioreactor.
Sample frequency and protocol	Baseline groundwater samples were collected prior to starting the recirculation system. Monitoring events occurred approximately 3, 7, 13, 18, and 24 months after recirculation started.
Quantity of material treated	Approximately 6.5 lb of TCE were removed from the 690,000 gal of groundwater recirculated through the bioreactor during the 2-year period. Additional TCE mass (estimated at 0.5 to 1 lb) was rapidly transformed within the bioreactor following bioreactor installation but prior to performance of the baseline sampling event and initiation of groundwater recirculation. The aquifer volume impacted during the pilot test is at least 11 times larger than the volume of the bioreactor. Calculating the total TCE mass removed in situ is problematic because the site is not a closed system.
Concentrations of untreated and treated contaminants	TCE concentrations in untreated groundwater ranged from 43 to 2,179 µg/L and from 0.1 to 20.2 µg/L in the treated groundwater. TCE concentrations decreased prior to the 2-year test. The total molar CAH concentration in shallow and deep monitoring wells remained relatively unchanged throughout the pilot test and ranged from approximately 15 to 29 micromolar. This was caused by the influx of new TCE mass from a nearby residual source into the monitored zone during the pilot test and the accumulation of TCE daughter products (DCE and VC).
Cleanup objective	90% reduction in total molar CAH concentration in shallow downgradient groundwater
Comparison with cleanup objectives	Geochemical conditions conducive to reductive dechlorination of CAHs were achieved, and biodegradation was enhanced. However, the cleanup objective was not met because of the presence of a residual TCE source area adjacent to the bioreactor that added new TCE mass to the monitored zone during the pilot test. The beneficial impact of the bioreactor decreased with increasing depth.
Method of analysis	VOCs were analyzed by a commercial fixed-base laboratory using USEPA Method SW8260B.
QA/QC	A QAPP was prepared for this project. Trip blanks, matrix spikes/matrix spike duplicates, and blind duplicates were collected.

4.1.1 TCE Concentration Trends

Figure 2 is a cross section of TCE concentrations in groundwater during the November 2003, June 2004, and November 2005 sampling events. Between November 2003 and June 2004, TCE concentrations decreased substantially at all wells in the vicinity of the bioreactor, including the upgradient wells. In December 2004, TCE concentrations began to rebound. It is hypothesized that this rebound reflects leaching of TCE from soil due to excessive rainfalls that occurred in October 2004 and November 2004. In June 2005, TCE concentrations at the shallow wells were low. For example, the TCE concentration at well SW5 was 5 μg/L in November 2005 as compared to 10,783 μg/L in November 2003. These data suggest that the bioreactor system affected the TCE contamination in the shallow groundwater zone. In November 2005, the TCE concentrations observed in the groundwater samples collected from the deep wells were of the same order of magnitude as the November 2003 results. The data indicate that the bioreactor had limited long-term impact on the TCE contamination in the deep groundwater zone.

In the end, bioreactor performance remains unresolved. To note, the bioreactor resulted in surprisingly rapid concentration changes. Relative to the baseline sampling event, TCE concentrations in shallow groundwater adjacent to the test cell were reduced by 96 to 99.9% during the five performance monitoring events. If the March 2003 TCE concentration (17,900 μg/L) for well WL250, located downgradient of the cell, reliably represents the downgradient groundwater quality immediately prior to bioreactor construction, then the bioreactor resulted in decreased TCE concentrations before the infiltration system became operational. The baseline sample from downgradient well SW5 had 10,783 μg/L TCE, which is approximately 60% of the March 2003 TCE concentration at well WL250. It is unclear whether the apparent change in the downgradient groundwater TCE concentration between March 2003 and November 2003 might be due to differences in the screened interval and pump placement during sampling or to natural temporal and spatial variability. With respect to long-term performance, an effective landfill bioreactor technology must be capable of addressing potential influx of upgradient contamination. The concentration rebound observed in the deeper wells suggests that the bioreactor cell was unable to address contaminant influx.

4.1.2 Total CAH Concentration Trends

Figure 3 shows the geometric mean total molar CAH concentrations in shallow groundwater adjacent to the bioreactor (wells SW1, 2, 5, and 6) over time. Shallow groundwater initially had a geometric mean total molar CAH concentration of 7,917 nanomolar (nM), and consisted of 49% TCE and 50% DCE. Over time, TCE was degraded; however, the total molar concentration of CAHs was higher than the baseline concentration during three of the five monitoring events, indicating an accumulation of TCE daughter products and influxes of new TCE mass into the shallow groundwater within the monitored area. During the first performance monitoring event in February 2004, the total molar CAH concentration in shallow groundwater adjacent to the bioreactor consisted of 99% DCE and less than 1% TCE and VC. By the second performance monitoring event in June 2004, the CAH content of shallow groundwater primarily consisted of VC (80%). From June 2004 to November 2005, VC consisted of 62 to 95% of the total molar CAH concentration in shallow groundwater.

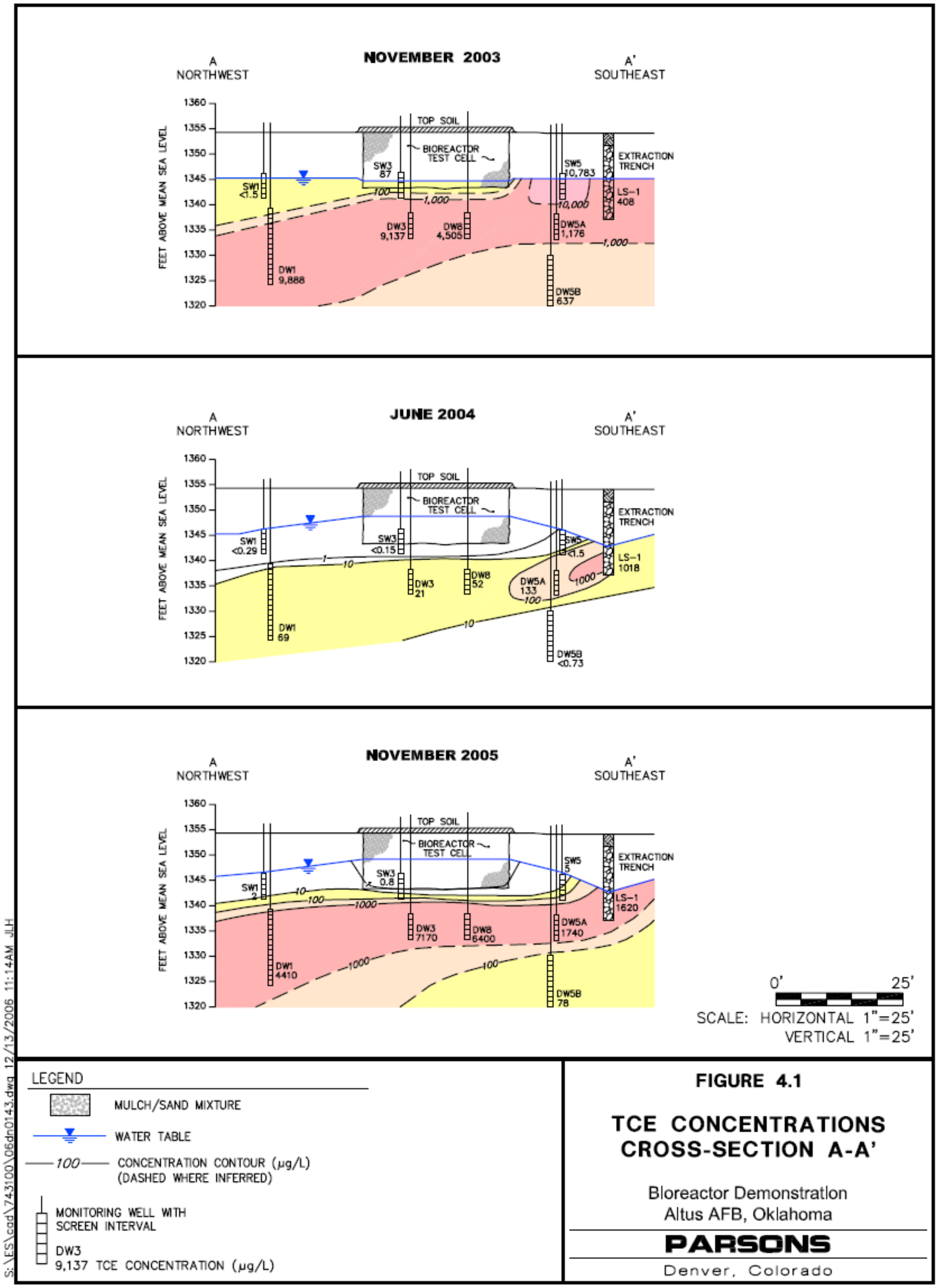

Figure 2. TCE Concentrations Cross Section A-A'.

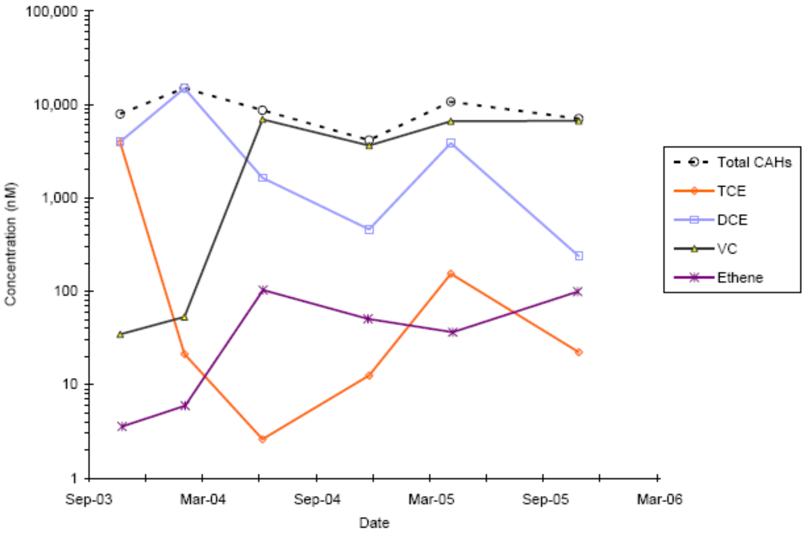

Figure 3. Molar Concentration Trends for Chlorinated Ethenes in Shallow Wells Adjacent to the Bioreactor.

Figure 4 shows the geometric mean chlorinated ethene concentrations through time for the deeper wells at the site (DW1, 2, 3, 4, 5A, 5B, 6A, 6B, 7, and 8). These wells were installed both adjacent to and through the bioreactor test cell, and are entirely screened below the base of the test cell. The total molar chlorinated ethene concentration in the deeper wells decreased by 52% from 13,406 nM in November 2003 to 6,420 nM in June 2004. A significant increase in TCE and total molar chlorinated ethene concentrations was observed after June 2004, suggesting that there was an influx of TCE into the area beneath the test cell after June 2004. The maximum geometric mean total chlorinated ethene concentration detected in the deeper wells was 20,084 nM in December 2004.

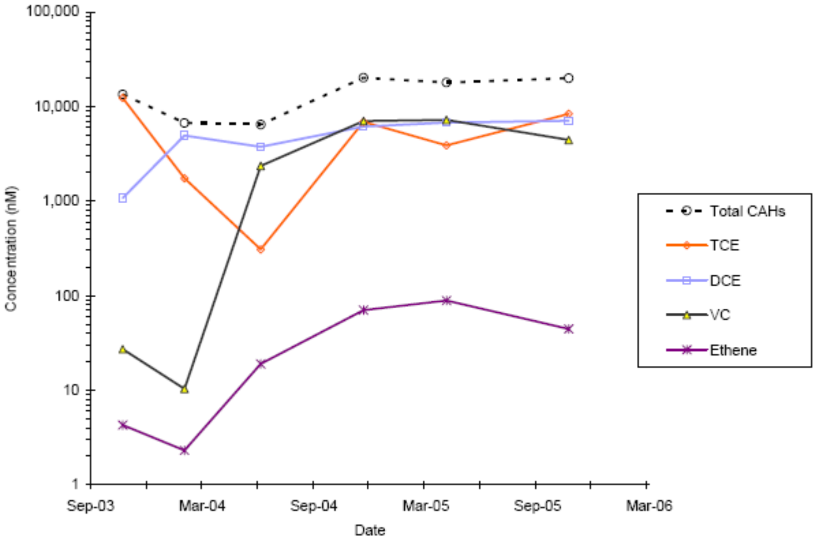

Figure 4. Molar Concentration Trends for Chlorinated Ethenes in Deeper Wells.

These data indicate that there is a continuing source of TCE in the vicinity of the bioreactor. The influx of TCE likely was caused by heavy precipitation that occurred in fall 2004, prior to the December 2004 groundwater monitoring event. The bioreactor test cell was virtually inundated with standing water during a visual inspection in November 2004. The accumulation of DCE and VC in the shallow aquifer is likely due to kinetic disparity where the intermediate dechlorination product is being generated faster than it is degraded, and not to an absence of appropriate dechlorinating microorganisms. These results highlight the importance of adequately delineating source areas prior to installing full-scale bioreactor systems, and indicate that soil excavation for source removal is a critical component of the technology.

4.1.3 Dissolved Organic Carbon Concentration Trends

Figure 5 is a graph showing the geometric mean DOC concentration trends for the recirculation system influent (LS-1), bioreactor interior (SW3 and 4), shallow aquifer adjacent to the bioreactor (SW1, 2, 5, and 6), and deeper aquifer adjacent to and beneath the bioreactor (all "DW" wells). The maximum DOC concentrations were observed in the bioreactor during the baseline sampling event, after installation of the mulch but prior to start-up of recirculation. The geometric mean DOC concentration measured in the bioreactor was 12,410 mg/L. The peak geometric mean DOC concentration for the shallow wells adjacent to the bioreactor was 114 mg/L, measured during the first performance monitoring event in February 2004. By the final performance monitoring event in November 2005, the geometric mean DOC concentrations in the bioreactor and adjacent shallow wells decreased to 32 and 19 mg/L, respectively. Figure 5 shows that the deeper wells had less of an increase in DOC and reached a maximum geometric mean DOC concentration of 30 mg/L in April 2005.

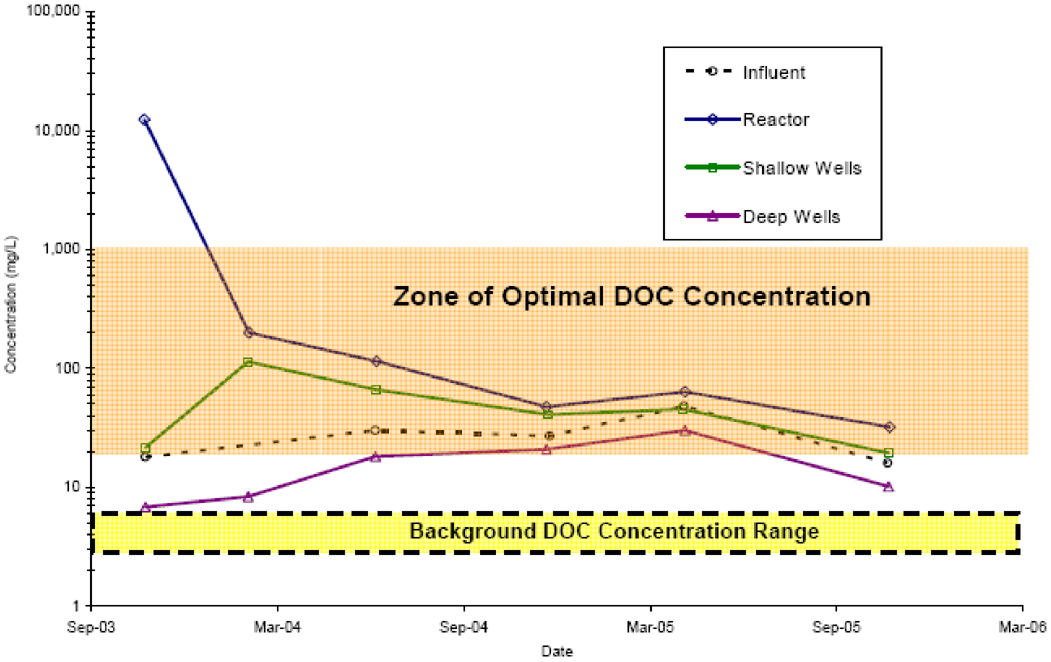

Figure 5. Dissolved Organic Carbon Concentration Temporal Trends.

Based on November 2003 (baseline) DOC concentrations in upgradient deeper wells, the background DOC concentration near the bioreactor is approximately 3 to 6 mg/L. DOC concentrations were elevated above the 20 mg/L threshold that is conducive to reductive dechlorination for approximately 6 months to a year in the deep wells beneath the bioreactor, and for almost the entire 2-year duration of the pilot test at the shallow wells adjacent to the test cell. These data suggest that, for this pilot test site, the pool of organic material required to maintain the DOC levels was depleted in approximately 2 years.

4.2 PERFORMANCE CRITERIA

The primary performance criteria for the evaluation of the recirculation bioreactor are contaminant reduction and geochemical/microbial enhancement in the saturated zone. The effectiveness of the bioreactor field demonstration was evaluated primarily using groundwater analytical results for samples collected from the monitoring wells installed up- and down-gradient from (based on the pre-recirculation groundwater flow direction), within, and beneath the test cell. The results from the five performance monitoring events were compared to the initial baseline sampling event and historical analytical data for nearby well WL250. The degree to which the bioreactor successfully enhanced the geochemical conditions of the saturated zone was assessed by comparing concentrations of the parent chlorinated ethene compound, TCE, and biodegradation daughter products over time, and by the degree to which concentrations of competing electron acceptors (e.g., sulfate) were reduced and microbial populations and concentrations of metabolic byproducts (e.g., methane, VFAs) and chloride were enhanced.

The secondary performance criteria were more qualitative and included identifying factors that affect the bioreactor performance, evaluation of system reliability and maintenance requirements, and evaluation of system scale-up constraints.

Table 4 presents the performance criteria and the actual versus expected performance for the demonstration.

4.3 DATA ASSESSMENT

Acceptable levels of data quality were achieved by following the sampling procedures outlined in “Procedures for Well Development and Sampling” (Appendix B) and the QAPP (Appendix C) in the Final Technical Report (Parsons, 2006).

Table 4. Expected Versus Actual Performance, Bioreactor Demonstration, Altus AFB.

Performance Criterion	Expected Performance Metric	Performance Confirmation Method	Actual
Geochemical and microbial enhancement in saturated zone	Reduction in DO, nitrate/nitrite, sulfate, and oxidation-reduction potential (ORP) levels and increases in methane, dissolved hydrogen, chloride, DOC, VFAs, PLFAs, alkalinity, ferrous iron, dissolved manganese, and hydrogen sulfide levels. Maintenance of near-neutral pH levels.	Comparison of performance monitoring results to baseline results; temporal trend analysis	• Increased DOC concentrations produced anaerobic, reducing conditions in the bioreactor and the aquifer. Increases in chloride, alkalinity, and metabolic by-products (methane, VFAs, dissolved manganese, ferrous iron) were observed. Sulfate concentrations were reduced. DOC concentrations suggest organic substrate depleted in approximately 2 years. • Biomass increased by as much as two orders of magnitude. • Increased concentration of anaerobic firmicutes bacteria that are responsible for fermentation of DOC and production of dissolved hydrogen.
Contaminant reduction	Reduction in parent solvent (i.e., TCE) concentrations, production of daughter products including ethene. The goal of this demonstration was a 90% reduction in the total molar concentration of CAHs as measured in the wells beneath and downgradient of the LF-03 test cell. Overall toxicity reduction in groundwater.	Comparison of performance monitoring results to baseline results; temporal trend analysis	• TCE reduced at well WL250, located between the bioreactor test cell and the groundwater collection trench and screened 8-18 ft bgs. • 96 to 99.9% geometric mean TCE removal efficiency for shallow wells outside the bioreactor during the five performance monitoring events. • 97 to 100% TCE removal efficiency within the bioreactor during the five performance monitoring events. • A 90% reduction in the total molar CAH concentration was not achieved in the wells beneath and downgradient of the LF-03 test cell. However, a 76 to 96% total molar CAH removal efficiency was achieved within the bioreactor during the five performance monitoring events. • In shallow monitoring wells adjacent to the test cell, the total molar chlorinated ethene concentrations were greater than the baseline concentrations during three of five performance monitoring events due to TCE daughter product formation (DCE and VC) and TCE influx from a continuing source.

Table 4. Expected Versus Actual Performance, Bioreactor Demonstration, Altus AFB (continued).

Performance Criterion	Expected Performance Metric	Performance Confirmation Method	Actual
Factors affecting technology performance	Excessive mounding in LF-03 test cell causing surface seeps. Evidence of aeration of collected groundwater in collection trench and/or distribution piping resulting in chemical precipitation and system fouling. Solar pump operates in a trouble-free fashion	Measurement of water levels in bioreactor; comparison of groundwater geochemistry between monitoring well samples and samples from collection trench sump and distribution line; observations of solar pump and recirculation system reliability	• Excessive mounding did not occur. • No chemical precipitation or system fouling was observed; however, in-line strainer required periodic cleaning to maintain flow of pumped water into recirculation lines. • Solar pump operated in a trouble-free fashion with no maintenance required. • Seasonally lowered groundwater temperatures in bioreactor appear to have resulted in decreased chlorinated ethene removal efficiency. • High sulfate concentrations likely decreased size of dechlorination treatment zone in aquifer and limited dechlorination effectiveness.
Reliability and maintenance	No breakdowns, routine periodic maintenance	Evaluation of operating parameters; experience from system operation, monitoring, and maintenance (OM&M)	• Solar pump operated without breakdown. • A leak in the recirculation system (from air release valve) was observed and fixed. Available data suggest that one or more additional small leaks were present and became more significant with time; this was alleviated by directing flow to the backup recirculation lines and cleaning the inline strainer. • No vendor or subcontractors were necessary for performing maintenance and repairs. Less than 2 hours per month of maintenance was required.

Table 4. Expected Versus Actual Performance, Bioreactor Demonstration, Altus AFB (continued).

Performance Criterion	Expected Performance Metric	Performance Confirmation Method	Actual
Scale-up Constraints and Technology Application	Readily scalable and applicable to other sites and contaminants	Experience from design and operation of the system	• Scale-up of this technology is feasible and would likely not pose significant problems. • Scale-up would likely require a longer and deeper extraction trench, multiple pumps, and larger piping. • More detailed hydrogeologic analysis may be necessary to ensure capture of potential daughter product plume without diluting the DOC concentrations. • Intermittent operation using a solar pump may not be desirable at some sites. Design may be modified to use a solar pump with battery array for longer pumping periods. • Solar pumping system not appropriate for areas with relatively low solar radiation or at sites where direct sun exposure is not possible. • Some landfills may be too hazardous to excavate. If necessary, the bioreactor design can be modified so that excavation does not extend into waste disposal zone. • This technology is not limited to landfill sites. It may be applied to source areas with contaminants other than CAHs. • Many sources of organic substrate are available. • Removal of source area is a critical component of this remedy, as evidenced by the influx of TCE during the pilot study. Full-scale implementation would require identification, delineation, and removal of source areas.

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5.0 COST ASSESSMENT

5.1 COST REPORTING

All relevant costs and related data were tracked and documented during the pilot demonstration to facilitate estimation of the full-scale costs of bioreactor design, installation, and OM&M. The total cost for the technology demonstration was $171,872. This cost includes $56,152 in start-up and capital costs, $2,880 in O&M costs, and $112,840 for monitoring during the 2-year demonstration.

Table 5 shows the estimated costs for construction and 2 years of OM&M of the 900-sq ft LF-03 recirculation bioreactor if operated as a full-scale implementation of the technology rather than a pilot test. For this estimate it is assumed that $50,000 would be spent on performing a preconstruction site characterization to define the TCE source location more accurately. The LF-03 pilot test demonstrated the importance of locating source areas to the success of the system. Groundwater monitoring could be reduced significantly for a full-scale application of the technology. It is estimated that the monitoring network could be sampled semiannually for $33,980 a year. The reduced OM&M costs would primarily result from reducing the number of wells monitored by approximately one-half, reducing the sampling frequency to semiannual, and limiting the target analytes to the primary indicators of the bioreactor performance (i.e., VOCs, and a limited number of geochemical parameters). Additional costs associated with the demonstration project such as the work plan preparation, ESTCP status reporting, and preparation of the final technical and cost and performance reports are not included in Table 5 as these costs would not normally apply to the full-scale implementation of this technology.

The major cost driver for the recirculation bioreactor technology is the size of the bioreactor cell, which directly impacts construction and material costs, and the disposal requirements for the excavated soil and debris. Equipment costs for the pilot recirculation system were approximately $4,000, a minimal component of the $171,000 capital and OM&M costs for the 900-sq ft bioreactor at Altus AFB. Approximately 40% of the capital costs incurred for the pilot bioreactor were for a construction subcontractor, labor for oversight and field engineering, soil disposal, and purchase of backfill materials. The single largest capital cost incurred was for installation of the performance monitoring network (34% of total capital costs).

The solar powered groundwater recirculation system used at LF-03 required very little maintenance and repair over the 2-year monitoring period. Similar results would be expected at other sites that use the same technology. Annual monitoring costs for a full- scale application of the recirculation bioreactor technology are expected to range from approximately $33,000 for a small system like the LF-03 bioreactor, to approximately $50,000 for a 1-acre system. Estimated monitoring costs assume semiannual sampling.

Table 5. Pilot Test Cost Summary, Bioreactor Demonstration, Altus AFB.

Cost Category	Sub-Category	Details	Total Cost ($)
Fixed Costs			
1. Capital costs	Planning/preparation	Review of historical data/site characterization	$50,000
	Mobilization/demobilization	Subcontractor mobilization, field crew travel costs	$4,450
	Design	Labor	$6,400
	Excavation of cell and trench	Subcontractor (370 CY cell and 30-ft-long trench)	$2,500
	Backfill of cell and trench	Subcontractor	$9,145
	Equipment purchase		
		Procurement	$500
		Groundwater pump	$1,055
		Solar power system	$1,225
		Pressure relief valve	$135
		Flow totalizer	$175
		Strainer	$10
		Pressure indicator	$30
		Piping (400 ft)	$350
		Vaults (4)	$80
		Lysimeter (2)	$60
	Field engineering		$4,800
	Disposal of soils	(175 CY)	$4,762
	Site cleanup		$675
	Performance monitoring network installation	16 wells, 1 soil vapor point	$16,800
			Subtotal: $103,152
Variable Costs			
2. Operation, maintenance, and monitoring	Year 1		$33,980
	Year 2		$33,980
			Subtotal: $67,960
		TOTAL:	**$171,112**

Notes: CY = cubic yard, ft = foot, hr = hour(s)

5.2 COST ANALYSIS

As noted in Section 5.1, the bioreactor cell dimensions and disposal requirements for the excavated soil/debris are expected to exert a substantial impact on the cost of full-scale implementation. To assess the potential cost impacts, the following scenarios were evaluated:

- Full-scale implementation scenario as shown in Table 5
    - Bioreactor dimensions of 30 ft x 30 ft x 11 ft
    - 175 cubic yards of soil disposed off site as nonhazardous waste (portion of soil excavated from the bioreactor cell location was retained on site)
    - 30-ft long, 2-ft wide, and 18-ft deep groundwater collection trench

- Scenario 1
    - Bioreactor and collection trench same dimensions as for pilot test
    - Offsite disposal of all soil excavated from the bioreactor cell footprint as nonhazardous waste

- Scenario 2
    - Bioreactor and collection trench same dimensions as for pilot test
    - Dense nonaqueous phase liquid (DNAPL) encountered in bottom 4 feet of bioreactor cell footprint (30 ft x 30 ft area). Excavation in this zone performed in Level C personal protective equipment (PPE), and associated soil/debris disposed offsite as hazardous waste
    - Offsite disposal of remainder of soil/debris excavated from bioreactor cell location as non-hazardous waste

- Scenario 3
    - Bioreactor dimensions are 100 ft x 100 ft x 11 ft
    - 100-foot long, 2-foot wide, and 18-foot deep groundwater collection trench
    - Offsite disposal of soil/debris excavated from bioreactor cell footprint as non-hazardous waste

- Scenario 4
    - Bioreactor dimensions are 100 ft x 100 ft x 11 ft
    - 100-foot long, 2-foot wide, and 18-foot deep groundwater collection trench
    - DNAPL zone with dimensions of 30 ft x 30 ft x 4 ft; excavation in this zone performed in Level C PPE, and associated soil/debris disposed of off site as hazardous waste
    - Off-site disposal of remainder of soil/debris excavated from bioreactor cell footprint as nonhazardous waste

- Scenario 5
    - Bioreactor dimensions are 200 ft x 200 ft x 11 ft

  - 200-ft long, 2-ft wide, and 18-ft deep groundwater collection trench
  - Offsite disposal of soil/debris excavated from bioreactor cell footprint as nonhazardous waste

- Scenario 6
  - Bioreactor dimensions are 200 ft x 200 ft x 11 ft
  - 200-ft long, 2-ft wide, and 18-ft deep groundwater collection trench
  - DNAPL zone with dimensions of 30 ft x 30 ft x 4 ft; excavation in this zone performed in Level C PPE, and associated soil/debris disposed of off site as hazardous waste
  - Off-site disposal of remainder of soil/debris excavated from bioreactor cell footprint as nonhazardous waste.

Scenarios 3 and 4 correspond to a bioreactor approximately one-quarter acre in size, while Scenarios 5 and 6 encompass slightly less than an acre.

Total net present value cost estimates for each scenario were developed with the following assumptions:

- Fifteen-year remedial time frame
- Replenishment of substrate with emulsified oil at Years 3 and 5 (based on the DOC data collected during the pilot test), followed by monitored natural attenuation to address residual contamination
- Annual OM&M costs based on the estimated cost of $33,980 per year (Table 5)
- Discount rate of 3.1 percent

The primary sources of unit costs were the 2005 RSMeans for Environmental Construction and the 2008 RSMeans for Heavy Construction. An inflation factor of 1.22, based on the Turner Construction Index was applied to unit rates obtained from the 2005 RSMeans. The total net present value calculated for each scenario is summarized in Table 6.

Table 6. Total Net Present Value of Bioreactor Scenarios.

Scenario	Total Net Present Value ($K)
Full-scale Implementation, Table 5	858
Scenario 1	967
Scenario 2	1,028
Scenario 3	3,144
Scenario 4	3,202
Scenario 5	9,587
Scenario 6	9,642

As shown in the above table, the total net present value increases substantially with bioreactor size, supporting the hypothesis that bioreactor cell dimensions are a primary cost factor.

Table 6 presents the breakdown of the total net present value into capital costs, OM&M costs, and periodic costs. With the 30 ft x 30 ft bioreactor cell dimensions, more than half of the total net present value is due to OM&M costs, while the capital cost is slightly greater than the total net present value of the periodic substrate replenishment. In Scenarios 3, 4, 5, and 6, OM&M costs are a minor component of the total net present value. While the primary cost component was the capital costs, the periodic costs of substrate replenishment also contributed substantially to the total net present value of these four scenarios. The cost analysis assumed two rounds of substrate replenishment. The degree to which substrate replenishment would be required during the O&M phase is likely to vary from site to site. The analysis indicates that this periodic cost, however, could contribute substantially to the total cost of the remedy.

The greatest contributors to the capital cost were off-site disposal (transport and tipping fee) and bioreactor backfilling. In Scenario 2, the assumed hazardous waste volume represented half of the soil identified for off-site disposal. The tipping fees and transportation costs associated with hazardous waste disposal increased the estimated capital costs by 24% as compared to Scenario 1 (same bioreactor dimensions; all soil/debris classified as nonhazardous). With Scenarios 4 and 6, the assumed hazardous waste volume represented a small fraction of the total volume identified for off-site disposal. Accordingly, the impact to the capital cost was less than in Scenario 2. The analysis emphasizes the importance of characterizing the bioreactor footprint prior to construction. If the source area is found to contain large quantities of soil/debris requiring off-site disposal as hazardous waste, capital costs could be higher than expected. On the other hand, if it is possible for the excavated soil to remain onsite, the capital costs could be substantially reduced.

This cost analysis indicates that the mulch bioreactor technology has the potential for incurring high costs, depending on the size of the source area and the type of waste encountered. While this approach may be appropriate for well-defined, small, isolated sources areas, it may not be the optimum approach for large landfills with multiple source areas.

5.3 INTEGRATION OF THE BIOREACTOR CELL INTO LANDFILL CLOSURE

The goal of this research was to investigate methods to accelerate the closure of unlined landfills. The bioreactor cell technology is intended to address a specific type of waste often encountered in landfills (i.e., chlorinated solvents). However, landfills typically contain other waste types in addition to chlorinated solvents. Unless the landfill contains only chlorinated solvent waste or the plan is to excavate the entire landfill during bioreactor cell construction, the technology cannot per se achieve landfill closure. For closure to be achieved, a cover would be required for any portions of the landfill where waste was left in place. In addition, the bioreactor cell technology may not treat all the potential groundwater contaminants. For example, groundwater beneath landfills often is contaminated with metals, such as arsenic and manganese, which are mobilized under reducing conditions. Until the substrate is depleted, the bioreactor cell could exacerbate commingled metals contamination.

The costing process for application of the bioreactor cell technology to a specific site should include the costs for the waste material outside the bioreactor cell footprint. If these costs are not included, the total landfill closure cost will be underestimated. Because of the need for any landfill remedy or corrective action to address all waste types, it is not expected that the bioreactor cell technology would decrease capital costs for landfill closure. The bioreactor cell technology must be implemented in conjunction with the excavation or covering of any waste material outside the bioreactor cell footprint. The potential cost benefit to be gained from the bioreactor cell would be decreased long-term monitoring (LTM) requirements if the dissolved phase contamination is dominated by chlorinated solvents or other contaminants amenable to remediation under anaerobic conditions. Even in this situation, a decrease in LTM requirements may not be realized due to the potential for commingled contaminants (e.g., arsenic, petroleum hydrocarbons) to linger under anaerobic conditions.

Because of the inability of the bioreactor cell technology to address commingled contamination, the technology may offer greater benefits at a non-landfill site with a well-defined chlorinated solvent source term and dissolved phase contamination.

6.0 IMPLEMENTATION ISSUES

6.1 COST OBSERVATIONS

Because the recirculation bioreactor was assembled with readily available components and conventional excavation techniques were used for construction, the actual costs incurred during the Altus AFB pilot test differed very little from the anticipated costs. Significantly higher costs would have been incurred if the excavated materials had been characterized as hazardous. Additionally, if hazardous or explosive conditions had been encountered during the excavation of the test cell, the cost would likely have been significantly higher than anticipated due to the need for implementation of contingency work procedures for health and safety reasons.

Analytical costs were a significant portion of the demonstration project budget and can be reduced for full-scale implementation of the technology. Analytical cost savings can be realized because 1) full-scale systems would not require the same density of groundwater monitoring points as the more research-oriented pilot-scale LF-03 bioreactor, and 2) the type and frequency of analyses for full-scale system performance monitoring can be reduced. At a minimum, the contaminants of concern and dissolved (or total) organic carbon should be analyzed to evaluate the remediation progress and strength/longevity of the carbon substrate. Less frequent (e.g., annual) monitoring of select geochemical parameters can reduce costs without sacrificing data quality objectives. Obtaining direct microbial evidence of biodegradation, including targeted gene analysis and PLFAs, is relatively expensive in terms of field labor and analytical costs and does not provide commensurate added-value for a long-term monitoring scenario. These specialized analyses should be reserved for troubleshooting system performance or other specific requirements rather than routine performance monitoring.

6.2 PERFORMANCE OBSERVATIONS

The original goal of the recirculation bioreactor was to reduce total CAH molar concentrations by 90% in shallow groundwater adjacent to the bioreactor. Because of the continuing upgradient TCE source and the slower biodegradation kinetics of VC and DCE compared to TCE, the CAH molar concentration increased over time. The organic mulch used in the bioreactor did provide a relatively long-lasting source of organic carbon (relative to soluble substrates such as fructose, lactate, or molasses) and produced conditions conducive to reductive dechlorination of TCE. The bioreactor was relatively effective at removing TCE and, to a lesser extent, DCE and VC, from the recirculated groundwater. A total CAH removal efficiency range of 76 to 96% was calculated for the five performance monitoring events.

The LF-03 pilot scale bioreactor at Altus AFB showed that the primary limitation for the technology was the inability to maintain significant levels of DOC and highly reducing conditions that are conducive to reductive dechlorination deeper than approximately 10 to 20 ft below the bioreactor. This limitation was likely due at least in part to the groundwater hydraulics at the site. The combination of the shallow depth of the extraction trench producing an upward hydraulic gradient and limited hydraulic head to produce a significant downward vertical gradient within the reactor caused the treatment zone at the site to be limited to shallower groundwater. Additionally, because the bioreactor was designed to be a long-lasting, slow-release source of organic carbon (i.e., relatively low DOC flux), the DOC was biodegraded (e.g., used to reduce high native sulfate levels) relatively close to the bioreactor cell rather than migrating deeper in the aquifer. Although it was intended that the mulch bioreactor provide a long-lasting source of DOC, the data indicated depletion of the leachable substrate in approximately 2 years.

In general, the reliability of the recirculation system during the 2-year operating period was good. The system as a whole was relatively simple, with few mechanical parts. The solar pump operated as planned with no mechanical problems. Operational data indicate that significant fouling of the drip irrigation system did not occur.

6.3 SCALE-UP

Scale-up of the recirculation bioreactor technology is feasible and, barring unforeseen conditions or circumstances, would likely not pose significant problems. The pilot-scale bioreactor installed at LF-03 was constructed with readily available off-the-shelf components. Each application of the bioreactor technology should be designed to site-specific factors such as depth to the water table (including seasonal or tidal fluctuations), and hydraulic conductivity of the aquifer. The carbon substrate for full-scale systems should make use of locally available organic materials to the extent practical. Scale-up would likely require a longer or deeper extraction trench, multiple pumps, and larger piping. More detailed hydrogeologic analysis may be necessary to ensure capture of potential daughter product plume without diluting the DOC concentrations. Consideration during the design of the bioreactor should be given to vehicle access to the site. Designated access roads may be desirable for larger-scale bioreactor systems and should be designed to avoid damage to the distribution lines. A significant scale-up constraint for the recirculation bioreactor technology may be the disposal of excavated materials from the site. The design of the bioreactor should be optimized by locating it within the source area in order to minimize construction and soil disposal costs.

6.4 OTHER SIGNIFICANT OBSERVATIONS

Full-scale implementation of the technology may include injecting amendments such as liquid carbon substrates (e.g., vegetable oil, lactate), nutrients, or bioaugmentation cultures. This can be readily accomplished via the recirculation system or dedicated injection piping. Design and construction of a bioreactor system with injection piping built into the system for adding amendments is more economical than retrofitting an existing system.

Vapor monitoring and potentially also vapor extraction may be required at sites located near buildings or utility corridors. Additional instrumentation that may be useful for evaluating the performance of the bioreactor cell and extraction trench are pressure transducers for automatic water level recording, thermocouples for monitoring temperatures in the cell, and a data acquisition system for remote monitoring of system parameters.

6.5 LESSONS LEARNED

The following bullets summarize the lessons learned for this demonstration project.

- Preconstruction site characterization, including adequate source area definition, is critical to the successful implementation of the technology.
- The technology may not be appropriate where the desired treatment zone extends more than approximately 10 to 20 ft below the water table.
- Persistent TCE source areas can lead to undesirable accumulation of daughter products (e.g., DCE and VC). This can potentially be remedied by bioaugmenting the bioreactor with a commercial microbial culture capable of completely degrading DCE and VC to ethene and periodically recharging the organic carbon content.
- Proper location and design of the groundwater extraction trench is a key component for preventing excessive downgradient migration of daughter products and for maximizing the vertical extent of the treatment zone in the aquifer.
- Although mulch is a relatively versatile and long-lasting carbon source, the relatively low rate of DOC flux from the mulch limits the distance the DOC can migrate from the bioreactor cell before it is biodegraded. The periodic addition of a liquid carbon substrate to the bioreactor (e.g., vegetable oil) may be an effective means of mitigating this limitation and extending the longevity of the carbon source. Spraying the mulch with a low-cost, slowly soluble, long-lasting substrate such as vegetable oil during bioreactor construction should be considered.
- The data indicated that the technology has limited ability to contain the dissolved contamination if source area(s) remain at the site.

6.6 END-USER ISSUES

The results of this project are directly applicable to future landfill and CAH spill site remediation decisions at Altus AFB and within the broader DoD and regulatory community. A full-scale recirculation bioreactor is funded for fiscal year 2007 construction at Altus AFB Site SS-17. The recirculation bioreactor concept is also being employed by the Army at Camp Stanley, Texas to introduce DOC into a fractured limestone aquifer contaminated with CAHs. The results of this pilot test may encourage the application of the bioreactor concept at additional DoD landfills as an alternative to traditional landfill closure techniques. To that end, it will be important to disseminate the results of this project within the DoD and USEPA. These findings could also have significant impact on the remediation and closure of thousands of industrial and municipal landfills that exhibit some level of CAH contamination. Publications in scientific and trade journals and presentations at industry and DoD conferences have been used to advance these concepts (Downey et al., 2004, 2005, and 2006).

Although the pilot-scale bioreactor was installed to test the technology at a TCE-impacted site at Altus AFB, LF-03, enhanced anaerobic bioremediation can also be applied to treat the following constituents (Parsons, 2004):

- Chlorobenzenes
- Chlorinated pesticides (e.g., chlordane) and polychlorinated biphenyls
- Chlorinated cyclic hydrocarbons (e.g., pentachlorophenol)

- Oxidizers such as perchlorate and chlorate
- Explosive and ordnance compounds
- Selected dissolved metals (e.g., hexavalent chromium)
- Nitrate and sulfate.

A primary concern for using a bioreactor or any enhanced bioremediation technology is the potential for production of toxic by-products such as VC at TCE- and PCE-contaminated sites. Therefore, adequate capture of more-toxic reductive dechlorination “daughter” products in groundwater exiting the bioreactor may be an important element of the bioreactor design process, depending on the prevailing reduction-oxidation conditions in the aquifer. The LF-03 bioreactor resulted in the production of daughter products; however, field demonstration results remain inconclusive as to whether there was an overall reduction in the toxicity of source area groundwater.

Additional concerns include the potential for subsidence of the mulch and accumulation of vapors in the vadose zone. The eventual subsidence of the mulch bioreactor may make this technology unsuitable for areas where future buildings and/or roads are planned. The potential for elevated concentrations of toxic or explosive vapors in the vadose zone should be addressed during the design of the bioreactor system.

6.7 APPROACH TO REGULATORY COMPLIANCE AND ACCEPTANCE

No special permits were required to install and operate the bioreactor at LF-03. However, digging permits were obtained from Altus AFB prior to intrusive activities, and Base access permits were obtained for the field personnel. In some states, permits may be required to re-inject extracted groundwater. Altus AFB personnel discussed this demonstration project with USEPA oversight personnel and obtained their support. Formal approval by the USEPA was not required.

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APPENDIX A

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